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Fusion and Fission of Light Nuclei with Angular Momenta near the Calculated Liquid-Drop Limit*

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Elemental yields have been measured for the nuclei produced in the reactions of 100- and 180-MeV ^{12}C on ^{27}Al. Fusion cross sections, including those followed by fission, are derived using charge conservation. At 180 MeV the apparent limiting angular momentum for fusion is $40\hbar$, in excellent agreement with a liquid-drop calculation. Fission does not account for more than 18% of the fusion cross section at 180 MeV, unless that fission is of an extremely asymmetric nature indistinguishable from the evaporation of small particles.

In several recent studies, the cross section for fusion of a heavy-ion projectile with a target nucleus has been determined by detection of the recoiling product nuclei.[1-3] At the high projectile energies employed in those experiments (~10 to 15 MeV/amu) the fusion cross sections are found to be well below the corresponding total reaction cross sections. Complementary experiments[4] indicate an increase in the probability of direct reactions in the same region where the fusion cross section is decreasing. However, since only a few of the possible direct-reaction products were observed, a substantial portion of the total reaction cross section remained unaccounted for.

It has recently been suggested[5] that there may be an appreciable cross section for fission of even the light elements when an excited nucleus is formed with very high angular momentum. In such a case the fission component might not be included in the fusion cross-section measurements as they are typically performed. The measured cross section would then be interpreted as the cross section for the formation of a nonfissioning fused nucleus.

This expectation of high probability of fission is based upon liquid-drop-model calculations[6] which indicate that the fission barrier decreases with increasing angular momentum. The angular momentum at which the fission barrier disappears is viewed as the maximum possible angular momentum at which fusion could occur. In view of the fact that the fission barrier is low for angular momenta near the limiting value, fission is predicted to be an important competing mode of de-excitation for nuclei produced with those angular momenta. The available data on fusion cross sections are indeed fairly well reproduced by evaporation calculations in which fission competition is calculated, taking into account the angular-momentum dependence of the fission barrier.[5]

To study the competition between various possible reaction mechanisms which can be important when heavy-ion projectiles have orbital angular momenta comparable to or greater than the limiting angular momentum calculated according to the liquid-drop model, we have measured the energy spectra and angular distributions of the nuclei produced in the reaction of 100- and 180-MeV ^{12}C projectiles with ^{27}Al. The maximum possible angular momentum of ^{39}K produced in the fusion of ^{27}Al with 100-MeV ^{12}C projectiles would be $\sim 40\hbar$,[7,2] which is equal to the limit calculated with the liquid-drop model. The maximum possible angular momentum of ^{39}K produced in the fusion of ^{27}Al with 180-MeV ^{12}C projectiles would be $\sim 52\hbar$.[7,2] From our data we determine the total cross section for fusion including the cross section for fission de-excitation of the fused system.

In our experiments a counter telescope was used to observe and identify the nuclei produced when the ^{12}C projectiles were incident on a 107-$\mu g/cm^2$ Al target. Since the first detector of the three-detector telescope was thin (1.5 or 8.4 μm), it was possible to determine, to low energies, the atomic number of even the heaviest nuclei produced in the reaction.[8] In addition, we performed experiments in which spectra of ions stopped in the first detector were obtained. This latter information was very useful in the determination of the shapes of the low-energy portions of the kinetic-energy spectra. Of the charged species produced in the target-projectile interaction, only those nuclei which receive very low momentum transfer from the projectile would go completely unobserved in these experiments. To test for C and O contamination of the target, we performed a series of irradiations of C and Mylar targets. From the resultant energy spectra we determined that contributions from C and O were negligible in the Al target irradiations.

At each angle, the energy spectra were extrapolated to zero energy, and the lab differential cross sections for each element were calculated. By integration of the lab differential cross sections, we have determined elemental yields for the observed product nuclei. These yields are presented in Figs. 1 and 2. We have also indicated in the figures the lab angles within which one quarter, one half, and three quarters of the total elemental yield is observed. Thus, the smaller those angles, the more forward peaked is the angular distribution. With reference to the data in the figures we make the following observations:

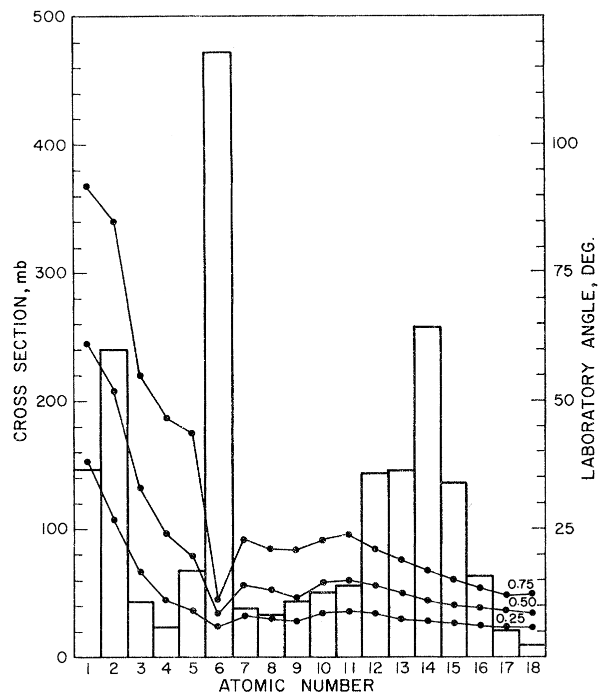

FIG. 1. Elemental yields for nuclei produced in the reaction of 100-MeV ^{12}C projectiles with ^{27}Al. Cross sections are indicated by a bar graph (left-hand scale). Cross sections for production of H and He have been divided by 10. Closed circles, angles within which fractional yields of 0.25, 0.50, and 0.75 of the total are observed (right-hand scale).

(1) Products with atomic number equal to or close to that of the projectile have angular distributions which are strongly forward peaked. These angular distributions apparently represent the predominantly direct mechanisms for reactions leading to those products. The dominant yield in this region of atomic number is that for carbon isotopes. Although it is not indicated on the figures, the inelastic scattering of ^{12}C accounts for the bulk of the carbon yield. The remainder of the yield consists of ^{11}C and ^{13}C, the neutron-transfer products.

(2) Products of atomic number ≥ 9 have similar angular distributions which become more forward peaked as the atomic number increases. Such a trend suggests that these nuclei are residual re-

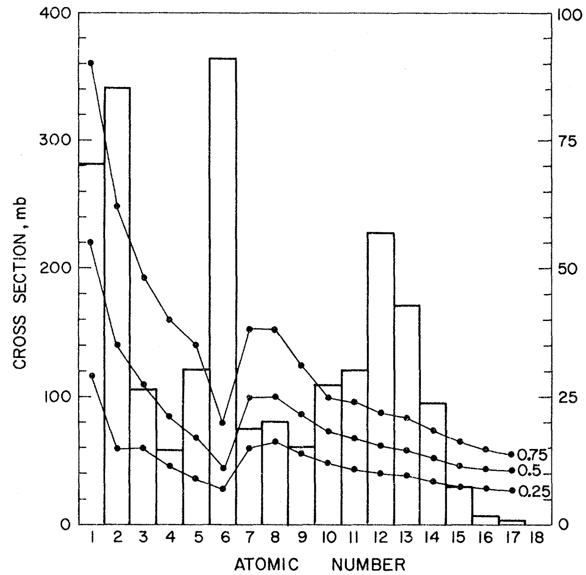

FIG. 2. Same as for Fig. 1, but for 180-MeV ^{12}C projectiles.

coiling products of the stepwise de-excitation of a ^{39}K compound nucleus. The energy spectra of these products are consistent with such an interpretation. The yield pattern of these products also appears consistent with that expected for a statistical de-excitation of the compound nucleus.

(3) The yield of H and He isotopes at each energy is greater than the total reaction cross section, and must represent multiple emission of these species during the de-excitation of heavier nuclei. At 180 MeV, the angular distribution of the He isotopes shows a strong forward peaking which was found in further study to be associated only with the ^4He isotope and not with ^3He which comprises about 10% of the total He yield. Based upon comparisons between the ^3He and ^4He angular distributions, we estimate that the additional forward-directed component of ^4He has a production cross section of 1 b. This is a much higher cross section than could result from the breakup of ^8Be (for which we expect cross sections similar to those for production of ^7Be and ^9Be) and presumably results primarily from projectile breakup.[9]

(4) At 100 MeV, the angular distributions of N and O nuclei are broader than those of C but slightly more forward peaked than those of higher-Z elements. The energy spectra for those ions extend to high energies, indicating that the yield of these elements results primarily from a direct reaction process. (b) At 180 MeV, the angular distributions of N and O nuclei fit very well within the trends established for the higher-Z products. The energy spectra of both (except for a small high-energy component of the N spectrum which results from ^{13}N, the proton pickup product of a direct reaction) are qualitatively very similar to those observed for the higher-Z products. The yields of O and N (even when the ^{13}N direct reaction product is excluded) are slightly greater than the F yield. This larger yield of N and O could indicate some selective mode of decay in the last stages of the de-excitation of the fusion nucleus or, alternatively, might signal the presence of another reaction mechanism.

In our experiment, the only nuclear reactions for which more than one product nucleus will be counted are those which involve nuclear fission or ejection of charged fragments. If we sum the yields of the observed products, temporarily excluding the H and He isotopes which must primarily represent light-particle emission from heavier species, we find that the total cross section for production of isotopes with $Z \geq 3$, with no correction for ^8Be emission, is 1608 mb at 100 MeV and 1637 mb at 180 MeV. These summed cross sections for $Z \geq 3$ products are very close to the expected total reaction cross sections[7,10] of 1550 and 1750 mb at 100 and 180 MeV, respectively. It appears therefore that relatively little double counting is done for $Z \geq 3$ products, i.e., that nuclear fission cannot account for a very large fraction of the total reaction cross section. This preliminary conclusion could be in error only if there were a high probability for production of excited nuclei which totally disintegrate into isotopes of H and He.

Since products from H through K could be observed in our experiment, we may use conservation of atomic number to determine the cross sections for fusion. We first write

$$\sigma_R = \sigma_{CF} + \sigma_D, \tag{1}$$

where σ_R is the total reaction cross section, σ_{CF} the fusion cross section, and σ_D the cross section for direct reactions (by which we mean all nonfusion processes). We define $\overline{Z}$ as the average observed atomic number per nuclear reaction. The experimental value of $\overline{Z}$ may be determined from the elemental yields as

$$\overline{Z} = \sum_Z \sigma_Z Z / \sigma_R, \tag{2}$$

where σ_Z is the cross section for production of a nucleus of atomic number Z. If we designate the total observed charge for fusion and for direct reactions as Z_{CF} and Z_D, we may write

$$\bar{Z} = (\sigma_{CF} Z_{CF} + \sigma_D Z_D)/\sigma_R$$

$$= [\sigma_{CF} Z_{CF} + (\sigma_R - \sigma_{CF}) Z_D]/\sigma_R. \quad (3)$$

For fusion processes, we can detect both the heavy fusion products and lighter charged particles ejected during the de-excitation step. Therefore we take Z_{CF} to be equal to 19, the sum of the target and projectile atomic numbers.

For direct reactions, we can detect the lighter partner of the interaction and any charged particles ejected during the de-excitation of either partner. The recoiling heavy partners of inelastic scattering and few-nucleon transfers, the predominant direct reactions, are not detected. Based upon these restrictions and upon the very high yield of C isotopes at forward angles, we assume a value of 6 for Z_D.

Using the elemental yield data in Figs. 1 and 2, and using the total reaction cross-section values of 1550 and 1750 mb,[7,10] we obtained 14.5 and 13.6 for the value of $\bar{Z}$ at 100 and 180 MeV, respectively. Substituting the appropriate values into Eq. (3) we find $\sigma_{CF} = 1.00$ b at 100 MeV and 1.02 b at 180 MeV. A change of Z_D to 5 or 7 will change these calculated values by no more than 65 mb. We estimate uncertainties of $\pm 10\%$ on these fusion cross sections.

Turning again to the data of Fig. 1 we note that at 100 MeV the summed yield of products with $Z \geq 9$ is 927 mb, which is in good agreement with the 1.00-b cross section calculated from charge conservation. This agreement—coupled with the fact that the energy spectra, angular distributions, and yield patterns of the $Z \geq 9$ products were entirely consistent with production in a stepwise de-excitation of ^{39}K—leads us to the conclusion that fission does not account for a large fraction of the cross section when ^{39}K is produced with 100-MeV ^{12}C projectiles.

At 180 MeV, the summed yields for $Z \geq 9$ is 834 mb. The inclusion of the N and O yields brings the sum to 989 mb, which agrees well with the value of the fusion cross section derived from charge conservation. Thus, the yield data alone indicate a maximum fission cross section of 181 mb, a value obtained by taking the difference between the summed yield of $Z \geq 9$ products and the calculated fusion cross section, where the products with $Z \geq 9$ are taken to be residual nuclei from de-excitation of ^{39}K by emission of small fragments and photons.

Since the energy spectra and angular distributions of the N and O nuclei agree with the trends established by the higher-Z products, we are probably justified in viewing the N and O as being produced primarily by the stepwise de-excitation of the fusion nucleus ^{39}K. However, in view of the slightly increased yield of these products, we do not rule out the possibility of some contribution from a fission mechanism.

In summary, the fusion cross sections reported here are total cross sections for fusion, including the cross section for fusion followed by fission. The value of 1.00 b for the fusion of ^{12}C with ^{27}Al at 100 MeV corresponds to a sharp cutoff limiting angular momentum[2,3] of $29\hbar$, well below the calculated limit of $40\hbar$. This result emphasizes the important role of nuclear dynamics in determining the fusion probability.[11,3] At 180 MeV, the limiting angular momentum corresponding to a cross section of 1.02 b is $40\hbar$. This limit at 180 MeV is equal to the calculated liquid-drop–model limit; but nuclear fission does not account for more than 18% of the fusion cross section unless that fission is of an extremely asymmetric nature and indistinguishable from evaporation of small particles.

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